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Long title:

Simplification of one-dimensional hydraulic networks by automated processes evaluated on 1D/2D deterministic flood models.

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Short title:

Automatic simplification of hydraulic networks for 1D/2D urban flood models

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ABSTRACT

Evaluation of pluvial flood risk is often based on computations using 1D/2D urban flood models. However, guidelines on choice of model complexity are missing, especially for 1D network models. This study presents a new automatic approach for simplification of 1D hydraulic networks (SAHM) using trimming and merging techniques, with performance evaluated in a 1D/2D case study. Decreasing the number of elements in the 1D model by 66% yielded a 35% decrease in computation time of the coupled 1D/2D simulation. The simplifications increased flow in some downstream branches and removing nodes eliminated connection to some areas. This promoted errors in 2D flood results with changes in spatial location of flooding in the reduced 1D/2D models. Applying delayed rain inputs to compensate for changes in travel time and preserving network volume by expanding node diameters did not improve overall results. Investigations on the Expected Annual Damages (*EAD*) showed that differences in *EAD* are smaller than deviations in the simulated flooded areas, suggesting that spatial changes are limited to local displacements. Probably, minor improvements of the simplification procedure will further improve results of the reduced models.

Keywords | Hydraulic network, 1D/2D urban flood model, computation time, flood damage cost, model reduction.

ABBREVIATIONS AND NOTATIONS

1D	One-Dimension(al)
2D	Two-Dimension(al)
CSI	Critical Success Index
DEM	Digital Elevation Model
EAD	Expected Annual Damage
GIS	Geographic Information System
NC	No Compensations – used when no compensations for volume and travel time have

been included in the simplified model.

SAHM Simplification Algorithm for 1D Hydraulic network Models

T###Mxxx Notation of models only trimmed by ### mm.

TxxxM### Notation of models only merged by ### metres.

T###M### Notation of simplified models both trimmed by ### mm and merged by ### metres.

27 **INTRODUCTION**

28 Hydraulic models of urban drainage networks have been used for decades to evaluate the resilience of an
29 area or test effects of new infrastructure. With the main purpose of evaluating drainage capacities, for long it
30 has been sufficient to simulate flows in the drainage network only. Naturally, these physically based
31 deterministic models are now also commonly used to support decision-making for climate adaption
32 structures and urban development plans (Field et al., 2012). However, climatic changes and urban
33 development are causing an increase in size and frequency of urban flooding leading to a need for local
34 measures to reduce the impacts (Field et al., 2012; IPCC, 2014). This means that overland flows must be
35 included in the hydraulic models (Henonin et al., 2013). Compared to 1D surface models, a more realistic
36 description of surface flow patterns is obtained by using coupled 1D-2D models (Leandro et al., 2009).

37 The coupling of a 1D network model and 2D surface model (1D/2D) has significantly expanded the
38 application areas of urban flood models and these models are now commonly used to predict the extents of
39 urban flooding (Henonin et al., 2013; Russo et al., 2015). The shift from 1D/1D to 1D/2D models
40 dramatically increases the computational demand (Henonin et al., 2013; Leitão et al., 2010; Van Dijk et al.,
41 2014). The computational demand is of high importance for applications in flood warning systems or
42 simulation of multiple scenarios (Henonin et al., 2013; Leitão et al., 2010; Meneses et al., 2015). Therefore,
43 numerous attempts of speeding up 2D simulations are described in literature including multi-layered coarse
44 grid simulations (Chen et al., 2012), reduced complexity models (McMillan and Brasington, 2007), and
45 using a cellular automata approach (Ghimire et al., 2013).

46 The extensive work and knowledge gathered on computation of 2D models showed promising results with
47 reductions from days and hours down to minutes. With no change in the 1D network model, the
48 computational demand of the 1D model thereby accounts for a larger share of the total computational
49 demand of the 1D/2D model. Naturally, the next step is to reduce the computational demand of the 1D
50 network models.

51 Numerous studies have been dedicated to improvement of 1D hydraulic network models using various
52 approaches including conceptual models (Wolfs et al., 2013) or simply reducing the number of elements in

the network (Leitão et al., 2010). However, few have looked into the effects on 2D surface model results when reducing the level of detail of the 1D network for a coupled 1D/2D model.

Simplification of hydraulic networks is often conducted manually or semi-automatically using a Graphical Information System (GIS). These procedures require numerous subjective decisions. Guidelines for network simplification are scarce and only a few unofficial documents on good practice exist, e.g. Wastewater Planning Users Group (2002). Errors due to wrongly or over-simplified models (models with structural deficits) have been widely neglected according to Del Giudice et al. (2015) who attempts to capture the combined errors of inputs and structural model errors in a stochastic term. However, structural model errors can be reduced by setting up procedures for how the model complexity can be lowered. Furthermore, an automated tool will enable a more consistent practice as well as reduce time and resources needed when implementing model simplification.

The purpose of this paper is to present an approach for automatic simplification of the 1D component in 1D/2D flood models. We apply two different methods for network simplification along with a combination making a third approach. The approaches include compensations for the simplifications. The performance of the simplified models is evaluated by comparing to a baseline consisting of the full 1D/2D model whereby further development of the approach is identified.

METHODS

Three common approaches to network simplification are identified in Leitão et al. (2010), denoted pruning, trimming, and merging of links and nodes, respectively. Pruning is the most conservative method of only removing small, short links along main branches. This method has a very limited impact on computational demand and is rather a method to improve numeric model stability. Pruning is also included in the more comprehensive trimming approach that consists of deleting whole branches of links below a threshold for e.g. diameter. Finally, merging involves joining multiple links to a single one by deleting nodes. Merging will maintain the extent of the network while trimming leads to the removal of the pipe network in some areas. Additionally, the approaches can be combined by merging links in an already trimmed model.

Simplification of large network models

An automatic simplification tool is developed, applying the approaches in a fast and efficient manner. The Simplification Algorithm for 1D Hydraulic network Models, SAHM (Löwe et al., 2017), is newly developed in the open source programming language Python and input to the tool is extracted from a MIKE Urban geodatabase. The structure of the main script is shown in Figure 1a. Prior to removal, the link or node must fulfil an extensive set of conditions. Using SAHM, simplification is completed within a few minutes, with an output ready for simulation without further modifications.

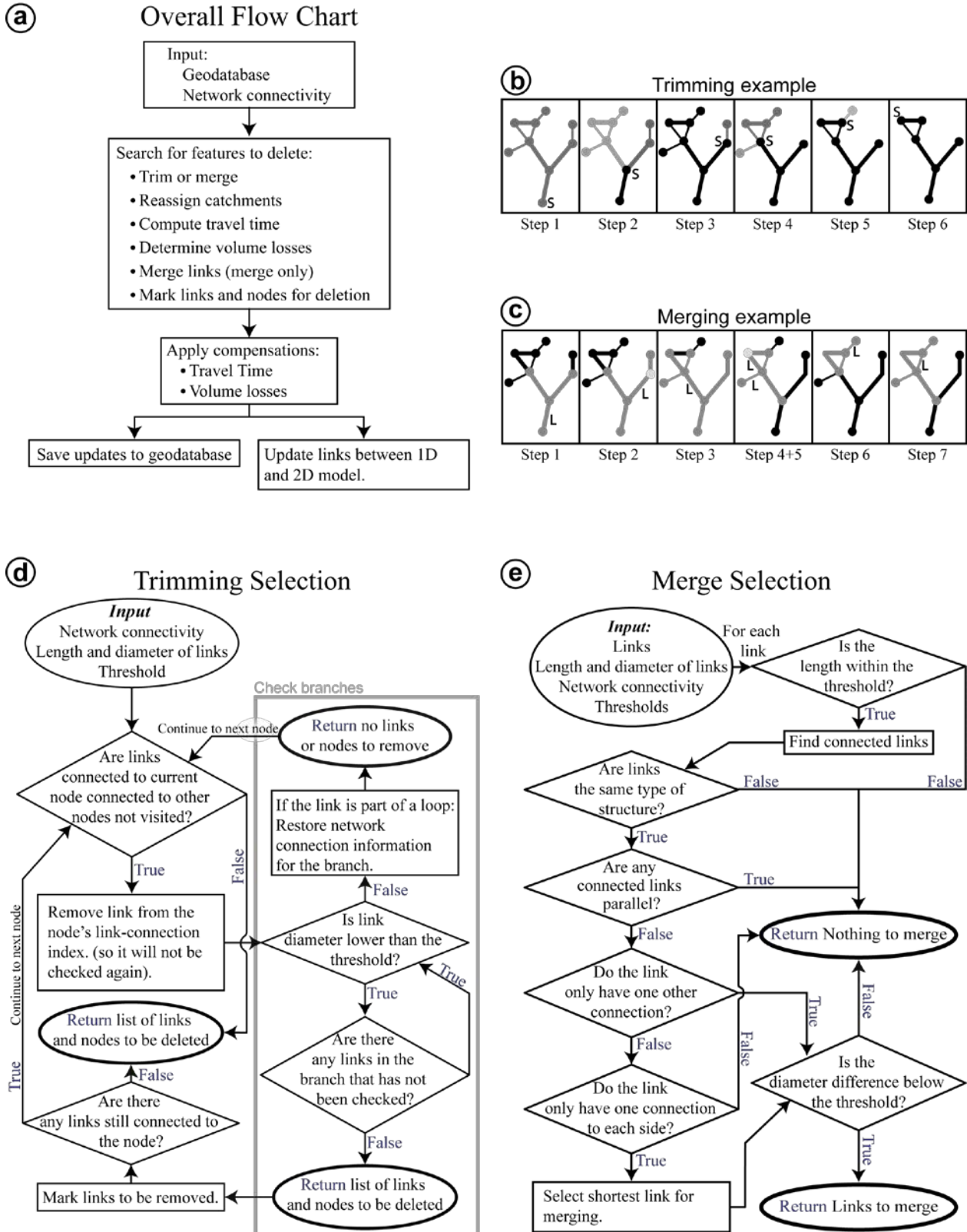


Figure 1: (a) Main structure of SAHM including different modules. (b) Procedure of trimming selection approach, removing nodes and links. S indicates the starting node in the search for branches to remove. Branches are considered individually as indicated by different colour shades. Only when all links in the branch fulfil the conditions, the branch is removed. Equally, loops are only removed if all links fulfil the conditions. If none of the branches fulfil the conditions, the search moves to the next upstream node. If multiple nodes exist upstream, these are considered as separate starting points. (c) Procedure of merging approach, removing nodes. L indicates the link from where the conditions of merging are checked with neighbouring link(s) one by one. Light grey nodes fulfil the conditions for

merging. (d) The approach for selecting links to delete when trimming using SAHM. (e) The approach for selecting links to merge in SAHM.

Trimming

The trimming module in SAHM performs the exclusion of pipes and branches below a certain diameter threshold defined by the user. This approach requires information of the connected branches. To fulfil this, the trimming algorithm is recursive, thus a starting point is defined from where the algorithm moves through the network as illustrated in Figure 1b. For each node, SAHM will check upstream branches and if all links within the branch are below the threshold diameter. If so, the branch is removed. Otherwise, the starting point moves one node upstream and the search is restarted from the new starting point. Figure 1d describes this procedure. In some cases, the branch contains a loop that may compromise the approach described to this point. To handle this, comparing nodes in the branch to previous start-nodes identifies a loop. A loop will only be removed when all links within the loop fulfil the conditions.

Merging

The merging module in SAHM joins two neighbouring links to one and removes the common node from the network. The condition for merging is a lower threshold on link length. Contrary to trimming, the merging approach only processes one link and its neighbouring links at a time as illustrated in Figure 1c. The approach for selection of links to merge is described in Figure 1e. An extensive set of conditions needs to be fulfilled before two links are merged. Initially, the length of the link is compared to the minimum length threshold. If the link is within the threshold, checks with neighbouring links begin, otherwise the search continues to the next link. Links are unsuitable for merging if they are parallel, have different type of structure, or have large diameter differences. The user defines the diameter difference threshold. In addition, a node cannot be removed if it is an intersection between three or more links. When a link can be merged with links to both sides, the shortest one is selected for merging. Since the link resulting from merging two very short links can be shorter than the threshold, the merging of the network is repeated several times with gradually increasing lengths until the specified threshold is reached. As indicated in Figure 1c, the total length of the pipe system is preserved, and hence the pipe length in the 1D simulation no longer corresponds to the physical length between the nodes in the reduced network

Compensations

Modifying the hydraulic network as described will change the characteristics of flow. We attempt to compensate for the changes by modifying the network volume and the travel times as described in the following.

123 *Reassigning sub-catchments and travel time*

124 When nodes are removed, the sub-catchments connected to the removed node are reassigned to the nearest
 125 downstream node. Thereby, runoff from these sub-catchments reaches downstream nodes earlier. We
 126 compensate for this effect by applying a time delay on the catchment runoff. The time delay t_L is
 127 approximated using the Manning equation to calculate the flow velocity, u , assuming full flowing conditions:

$$t_L = \frac{L}{u} = \frac{L}{M \cdot R_h^{2/3} \cdot S^{1/2}} \quad (1)$$

128 where t_L is flow time for a given link with Manning number M [$\text{m}^{1/3}/\text{s}$], hydraulic radius R_h , slope S , and
 129 length L .

130 Links with no or very low slope in the overall flow direction are assigned too long time delays when using
 131 this approach, since the acceleration, pressure and momentum descriptions from the Saint-Venant equations
 132 are neglected in the Manning equation used for the velocity approximation. Therefore, a threshold for
 133 minimum velocity is introduced for u in Equation 1. The threshold of minimum velocity has been defined to
 134 0.15 m/s based on Wallington charts (Butler and Davis, 2011). If the computed velocity for a link is below
 135 this threshold, the velocity of the upstream neighboring link is applied if this exceeds the threshold.
 136 Otherwise the threshold value is assumed as the velocity for the link in the estimation of time compensation.

137 The total time delay for each catchment, t_T , is computed as the sum of flow times for all links between the
 138 newly assigned network node and the original as:

$$t_T = \sum_{k=1}^n t_{L,k} \quad (2)$$

139 for the n links on the flow path, each with a flow time t_L . The total time delay is implemented by assigning a
 140 time delayed rainfall time-series to each sub-catchment.

141 *Volume losses*

142 When parts of the network are removed during simplification, the physical volume of the simplified network
 143 is smaller than that of the original network. With lower storage in the hydraulic network, water might be
 144 stored in the surface compartment causing flooding and provoke errors in simulated surface flooding. We
 145 compensate for volume losses by increasing the volume of nodes downstream from removed elements.
 146 Thereby, we maintain the maximum flow rate of the remaining links in the network. The total volume
 147 compensation V_c is calculated for each deleted pipe and node and summarised for the branch that is removed
 148 as:

$$V_c = \sum_{i=1}^n V_{L,i} + \sum_{j=1}^m V_{N,j} \quad (3)$$

150 where V_L and V_N are volume of the i^{th} link and j^{th} node respectively which is summarised for the n links and
 151 m nodes on the flow path giving the total compensation volume, V_c .

152 The total volume compensation V_c is added to the volume of the existing node, V_{node} , where compensations
 153 are implemented, and a new diameter, D_{new} , of the node is calculated as follows. Maintaining the height of
 154 the node, h_{node} , prevents changes of the maximum pressure head.

$$D_{new} = 2 \cdot \sqrt{\frac{V_{node} + V_c}{h_{node} \cdot \pi}} \quad (4)$$

155 In the trimming procedure, the volume compensation applies to the node where the deleted branch was
 156 attached. In the merge procedure, the diameter is changed in the node immediately downstream of the
 157 merged links.

158 **Assessing performance of the simplified models**

159 The simplified models are compared to the baseline model by means of traditional metrics such as
 160 computations time, hydrographs and mass balances. We also introduce two metrics that assess the
 161 importance of the spatial distribution of the model errors in their typical use, i.e. calculation of hazard maps
 162 and overall risk of flooding in the catchment. The metrics are described below.

163 To quantify the spatial errors of the hazard maps, we use contingency tables for each simulation comparing
 164 hits (overlapping pixels), misses (only flooding in baseline) and false positives (only flooding in simplified
 165 model). To summarize the results across the many models we use the Critical Success Index (*CSI*)
 166 introduced by Bennett et al. (2013):

$$CSI = \frac{hits}{hits + misses + false\ positives} \quad (5)$$

167 Flood risk is often summarized as the Expected Annual Damage (*EAD*) (Zhou et al., 2012). The *EAD* is
 168 computed from the damage costs and hence differences in *EAD* will indicate the ability of the simplified
 169 models to generate results that are correct on the catchment level in relation to decision-making.

170 The *EAD* is calculated as (Olsen et al., 2015):

$$EAD = \frac{1}{2} \sum_{i=1}^n \left(\frac{1}{T_i} - \frac{1}{T_{i+1}} \right) (D_i + D_{i+1}) \quad (6)$$

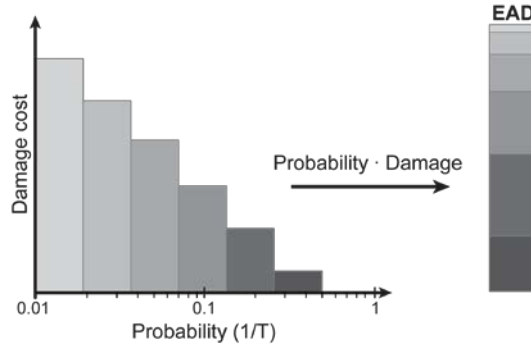
171 where T_i denotes the i^{th} return period being considered and D_i the total damage corresponding to return
 172 period T_i . Throughout all analyses return periods of 2, 5, 10, 20 and 100 years are used as recommended by
 173 Olsen et al. (2015). The total cost of flood damages are in this study calculated as a function of water depth
 174 for roads and buildings of both residential and commercial categories. For residential buildings, we further

175 distinguish between structural and content damages in the building. The costs and depths used in the damage
 176 functions are specified in Table 1.

177 Table 1: Thresholds for damages to different types of structures and costs. Numbers in brackets specify the water depth where the
 178 maximum damage cost occurs. Damage cost are obtained from Olesen et al. (2016).

Type	Threshold for damage	Cost range
Building – Commercial	10 cm (210)	162-852 AUD/m ²
Building – Residential		
Content damage	10 cm (300)	7,200-53,400 AUD/building
Structural damage	20 cm (300)	40,751- 190,171 AUD/building
Road	30 cm	3.71 AUD/m ²

179 With the damages calculated for multiple return periods, we use Equation 6 to calculate the EAD, as
 180 illustrated in Figure 2.



181
 182 Figure 2: Concept of EAD calculations. Equation 6 is used to calculate the area under the damage curve by interpolating between the
 183 damage costs determined for different return periods.

184 CASE STUDY

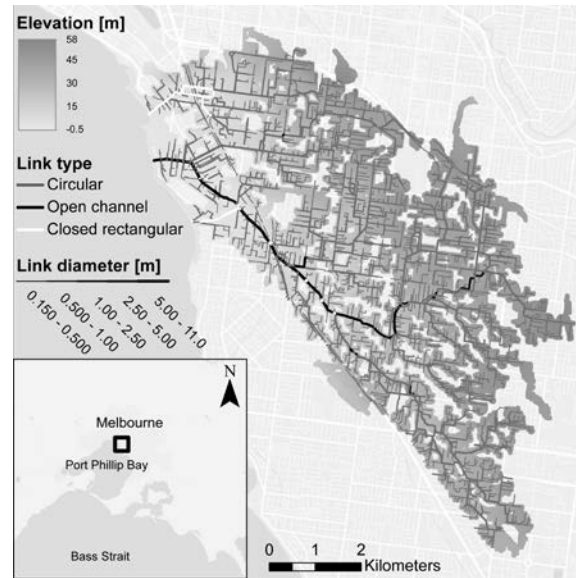
185 A 1D/2D urban flood model is used for testing SAHM. The model is set up in MIKE FLOOD and covers the
 186 Elster Creek catchment located in the suburbs of Melbourne, Australia (Figure 3). The area has recently
 187 experienced several large floods (Victoria State Government and Melbourne Water, 2016). The 1D network
 188 model contains 10,415 links, 10,011 nodes and 12,113 sub-catchments covering 48.7 km² including 19.6 km²
 189 impervious areas. The 2D surface is built from a mesh with 399,257 pixels of 10x10m and has been limited
 190 to areas where flow on the surface may occur to reduce computation time. Therefore, the mesh covers only
 191 40 km² of the catchment. Simulations are performed using a time-step of 2 seconds, both for the 1D network
 192 model and for the 2D surface model, in all considered scenarios.

193 The fully dynamic Saint-Venant equations are used for calculating flow in the 1D network via the 6-point
 194 Abbott-scheme. Flow in the 2D model is simulated using the full shallow water equations with a higher order
 195 numerical scheme and a finite volume method. For additional information on the 2D solution scheme used in

196 MIKE FLOOD, see DHI (2014) and DHI (2015). The two models are linked at each node using a virtual
 197 orifice for calculation of water exchange.

198 The hydraulic network primarily consists of circular links draining most catchments. A large open channel
 199 drains the area from mid-west to the northwest as the main outlet to the sea. Two additional outlets are
 200 located north and south of the main outlet. Both of these are closed rectangular channels with the southern
 201 one connected to the open channel, while the other drains the northern part of the network. The northwest
 202 part of the catchment is a low-lying area exposed to flooding from high sea levels. In this study, the sea level
 203 is kept constant at an elevation of 0 metres as we focus on flooding from the drainage system only. The
 204 upstream part of the catchment is steeper and flooding in this area is caused by precipitation only.

205 A baseline is produced from model simulations with different rain inputs. Design rain inputs with return
 206 periods of 2, 5, 10, 20 and 100 years were obtained from Australian Bureau of Meteorology (BOM, 2016)
 207 and are used for simulation. To obtain an indication of the uncertainty of the simulated flood extent resulting
 208 from other sources than simplification we have increased and decreased the rain volume by 23%,
 209 corresponding to the overall uncertainty of runoff according to Hansen & Liu (2004).



210
 211 Figure 3: Skeletonized drainage network and elevation of the case study area in Southern Melbourne, Australia.

212 Table 2 gives an overview of the 1D models used for simulation in the baseline and after simplification. The
 213 simplified models are denoted as T###M### with T denoting a model where links smaller than this threshold
 214 diameter in mm were trimmed, while M denotes where links shorter than the threshold in metres were
 215 merged. The notation xxx marks that either the trimming or merging module is not used for the
 216 simplification. Further, some models are denoted with “NC” as an abbreviation for No Compensations, thus
 217 no time and volume compensations have been implemented in these models. As a measure of the level of
 218 simplification, we use the network reduction factor, *NRF*:

$$NRF = \frac{\text{Elements in simplified model}}{\text{Elements in baseline}} \quad (7)$$

219 The 2D surface model is identical for all 1D/2D models, hence changes are only applied to the 1D network.

220

Table 2: Model data for baseline and simplified hydraulic 1D network models.

Model	Links	Nodes	Total length of links	Network reduction factor
Baseline	10415	10011	477 km	1.00
Merged				
TxxxM035	9421	9017	477 km	0.90
TxxxM050	8596	8192	477 km	0.82
TxxxM075	7832	7428	477 km	0.75
TxxxM100	7466	7062	477 km	0.71
TxxxM100-NC	7466	7062	477 km	0.71
Trimmed				
T300Mxxx	8857	8469	412 km	0.85
T400Mxxx	6938	6576	332 km	0.66
T500Mxxx	5551	5230	277 km	0.53
T500Mxxx-NC	5551	5230	277 km	0.53
Trimmed & subsequently merged				
T300M035	7998	7610	412 km	0.76
T300M050	7317	6929	412 km	0.70
T400M050	5597	5235	332 km	0.53
T400M075	4724	4362	332 km	0.44
T500M075	4416	4095	277 km	0.42
T500M100	3642	3321	277 km	0.34
T500M100-NC	3642	3321	277 km	0.34

221

222 **Simulation Environment**

223 The simulations were conducted using the MIKE FLOOD Message Passing Interface (MPI) limited to 7
224 threads on a HP EliteDesk 800 G2 TWR with Intel i7-6700 3.40 GHz CPU and 16 GB RAM.

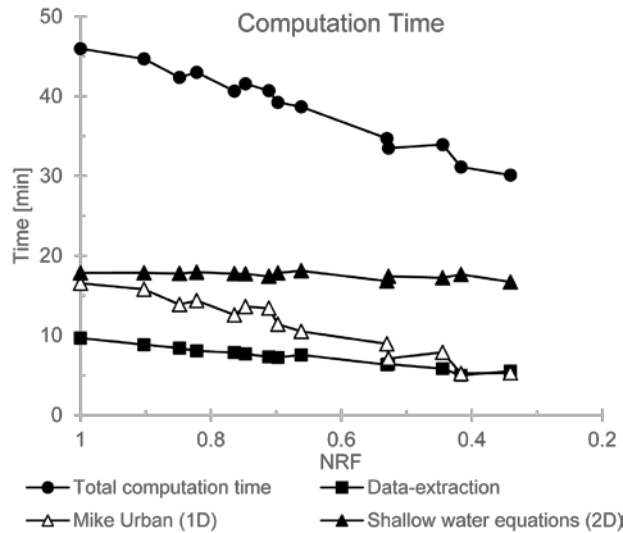
225 **RESULTS**

226 **Computation time**

227 In Figure 4, average computation time for the five rain events is shown for each considered model. The
228 overall computation time decreases with the *NRF*. The computation time for 1D calculation and data-
229 management decreases while the 2D calculations requires the same computation time throughout the
230 different model setups. For the baseline scenario, the simulation time is 16.6 minutes for the 1D model, 17.9
231 minutes for the 2D model and an additional 11.5 minutes for data management, combining into 46 minutes.
232 Data management consists of MPI-processes and loading/saving results between time steps. The
233 computational demand for data management decreases when simplifying the model as a result of smaller file
234 sizes. Using SAHM, the computation time of the coupled 1D-2D simulation is decreased by up to 35%. The

235 computational effort for the 1D simulations only is decreased by 68%. The reduction in computation time of
 236 the 1D hydraulic network model thus provides a significant overall decrease in computation time for the
 237 1D/2D flood model. With a higher resolution 2D surface, the 1D simulation will account for a smaller part of
 238 the overall computation time and hence the reduction will be less significant than in the case presented here.

239



240

241 Figure 4: Computation time of the baseline and simplified models. The computation time depends on the number of model elements
 242 hence the network reduction factor (*NRF*) is used for the horizontal axis. The computation time decrease with the number of elements in
 243 the 1D hydraulic network model due to both faster 1D calculations and fewer data to load and save during simulations. The 2D
 244 computation time is constant for all models.

245 1D Hydrographs

246 Hydrographs from the 1D hydraulic network model are inspected to locate potential changes in flow
 247 characteristics after simplifying the network.

248 Four examples are shown in Figure 5a-d at different locations in the network. Along main branches in Figure
 249 5a-c, the flow is over- or underestimated, thus higher or lower volumes are transported in the network.
 250 Especially the merged models lead to overestimation of the flow capacity of the 1D network. An explanation
 251 might be the reduction of head-losses from manholes, leading to lower energy losses. A strategy to
 252 compensate for this phenomenon may be decreasing the manning-number of the remaining links to
 253 compensate for the reduced energy loss. However, the explanation may also be that the removal of nodes in
 254 low-lying areas may lead to higher pressure gradients because there is no communication with the surface to
 255 reduce the pressure in the links.

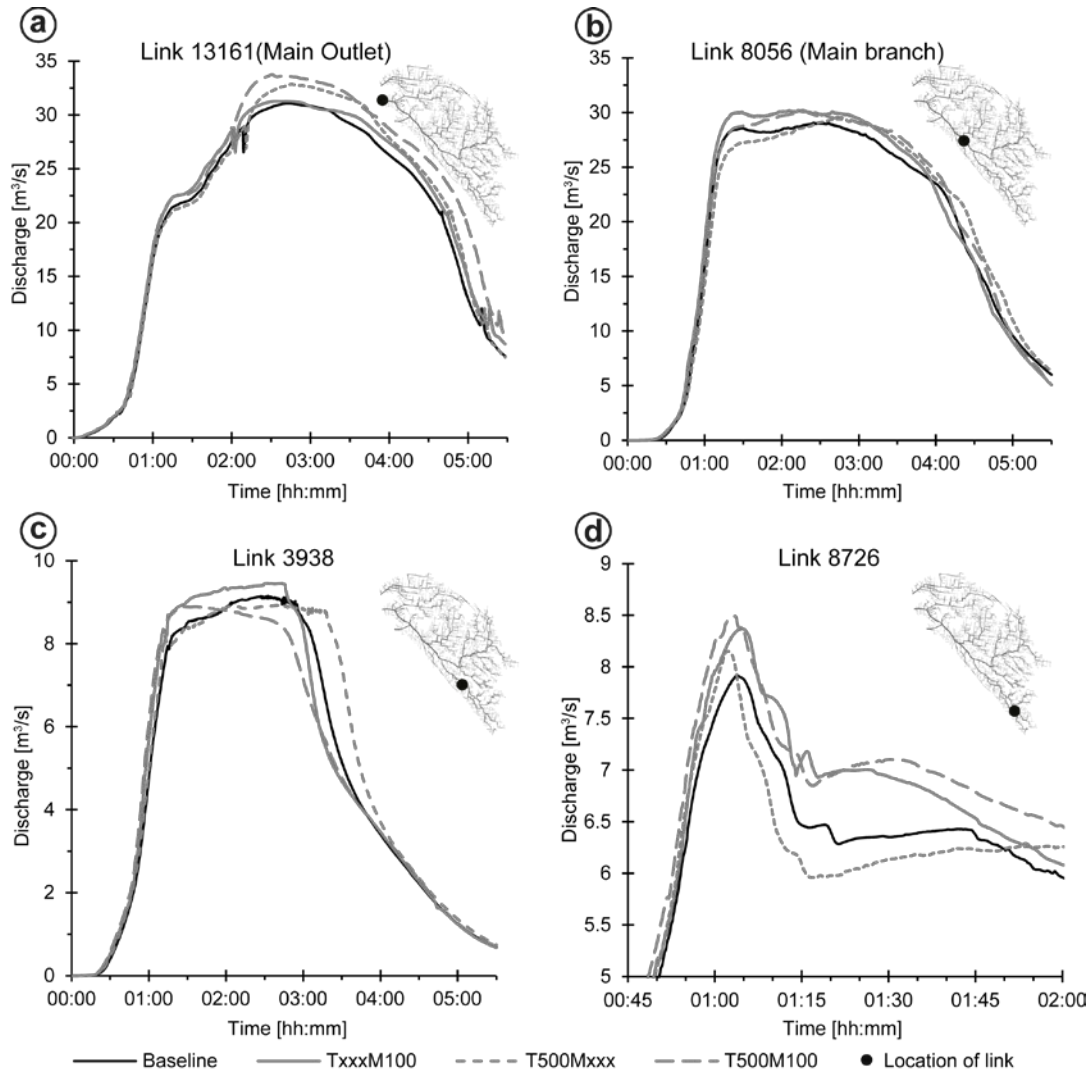


Figure 5: Hydrographs from the 1D hydraulic network model at a return period of 20 years for the baseline and most simplified models of the three approaches. The location of each link is indicated by a black dot on the small map in the top right of each sub-figure.

The hydrographs for an upstream link (Figure 5d) suggest that the simplified models slightly overestimate peak flows while the timing of peaks varies slightly. The TxxxM100 model is delayed by a minute while the T500Mxxx and T500M100 models peak a few minutes early. The time variations are smaller than in the models without compensations (not shown), thus the time compensation works as intended with improved fit of the initial peak to the baseline even at places where trimming has removed a large part of the network. The Manning Equation, used for calculation of the time compensations, describes flow processes in a more simplified manner than the Saint-Venant equations, leading to the small variations in peak time. After 2-4 hours of the simulation period, the flow is in many cases not as accurate with the decline starting earlier or later than the baseline. This may also be caused by changes in the surface flooding when storage and flow-paths change from the baseline.

269 **1D/2D water exchanges**

270 The outflow volume from the 1D network to the 2D surface models is illustrated in Figure 6 for 2, 5, and 20
271 year return periods. For the two-year return period, the volume exchange shows substantial increases when
272 merging is applied, with up to 380% exceedance of the baseline. The actual volume exchange is small
273 compared to the ten to hundred-year events, because for these events all the volume in the 1D model is fully
274 utilized. Simplifications of the 1D network then have only little impact on the simulated surface flooding.
275 For larger return periods there appear to be no differences between trimming and merging of the models.
276 However, for return periods up to 10 years the results indicate that merging is more important for the
277 combined 1D/2D model result because the removal of (downstream) nodes may lead to higher pressure and
278 hence a higher water exchange with the surface of the model. This tendency is exclusively observed in
279 models compensated for volume losses, while non-compensated models (not shown on Figure 6) maintains
280 water exchanges similar to the baseline. Increasing the node diameter thus significantly affects the water
281 exchange calculated by the orifice equation and leads to larger water exchanges.

282 Except for over-estimation of the volumes of the merged models for low return periods, there are no general
283 tendencies to observe with respect to the amount of simplification. For some return periods, higher degrees
284 of model simplification lead to smaller changes than lower degrees of model simplification and vice versa.

285

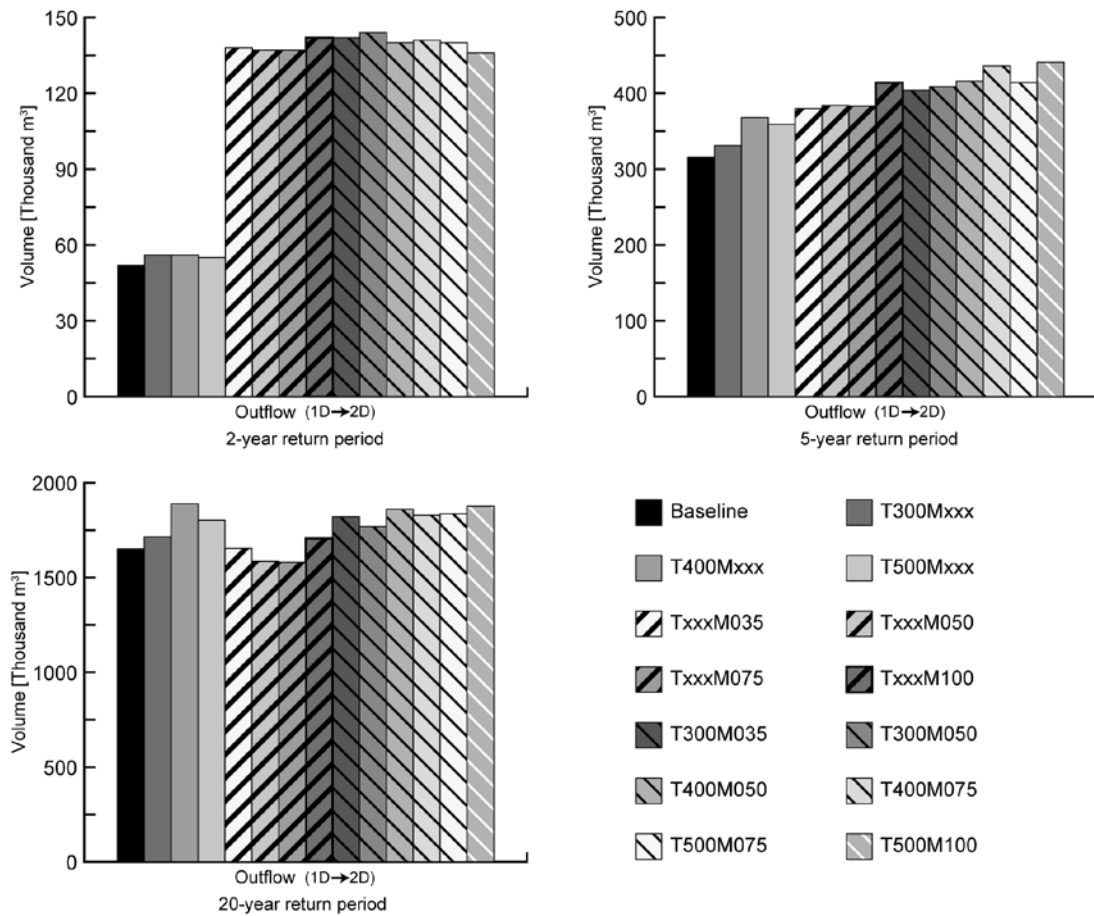


Figure 6: Water outflow from 1D network to 2D surface for return periods of 2, 5 and 20 years. Please note the different vertical scales.

Spatial distribution of the model errors on the surface

The impacts of simplification in the 1D network model on the 2D surface results are presented in the following section.

In Figure 7, the flooded surface area is shown for each return period as well as the baseline variation describing the inherent uncertainty of urban drainage calculations (Arnbjerg-Nielsen and Harremoës, 1996; Hansen and Liu, 2004). All simplified models underestimate the flooded area for all return periods. However, the changes are small compared to the baseline variation. The maximum water level of the reduced models is lower than the baseline for return periods of 2-20 years, but higher for the return period of 100 years despite showing similar tendencies on 1D/2D water exchange as the 20-year event in Figure 6. With increased water volumes on the surface, the results show that intensity of flooding has increased at places where flooding is already occurring. Meanwhile as seen in Figure 8, other areas are no longer flooded since they are no longer connected to the pipe network. In spite of rather accurate hydrographs in the 1D model, the spatial location of the nodes relative to depressions has a large effect on the flooding simulated in the 2D surface model.

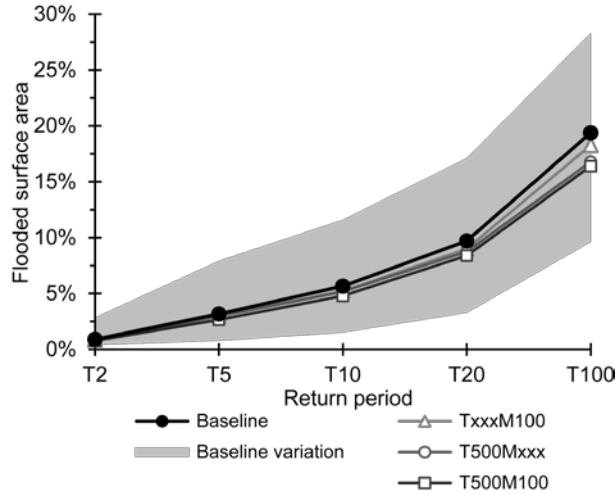


Figure 7: Flooded surface area as percentage of the total area of the mesh. The simplified models all underestimate the flooded area but do not exceed the reference variation computed via a 23% change in runoff from Hansen and Liu (2004).

The difference in spatial distribution of flooding is illustrated in Figure 8 as spatial hits, misses and false positives for the most simplified models, along with the maximum water depth of the baseline during a 100-year event. As shown in Figure 8b-d, the trimming approach may cause deletion of connections in locations where the full 1D model surcharges, whereby the water will surcharge at the nearby branches in the reduced model. The merging approach also leads to changes in the spatial distribution of flooding but to a much lesser extent than trimming.

Figure 9 show the *CSI*, summarizing hits, misses and false positives for the simplified models. All values are relative to the baseline and calculated as an average over all simulated return periods. The errors increase as the network reduction factor decreases. The most simplified models maintain a hit-rate of 57%, while misses and false positives are around 43% and 33% respectively. In general, the trimming approach causes larger spatial errors than the merging approach, even though the mass balance indicates that merging has the highest impact on the water exchange. Errors frequently occur in the outermost branches where trimming removes the connection to certain areas that may be flooded. Additionally, more severe flooding is simulated along main branches in all of the simplified models. Increased flooding along main branches implies a higher inflow from the smaller branches upstream, potentially linked to neglected energy losses in the removed features of the system and reduced storage of water on the surface in upstream areas.

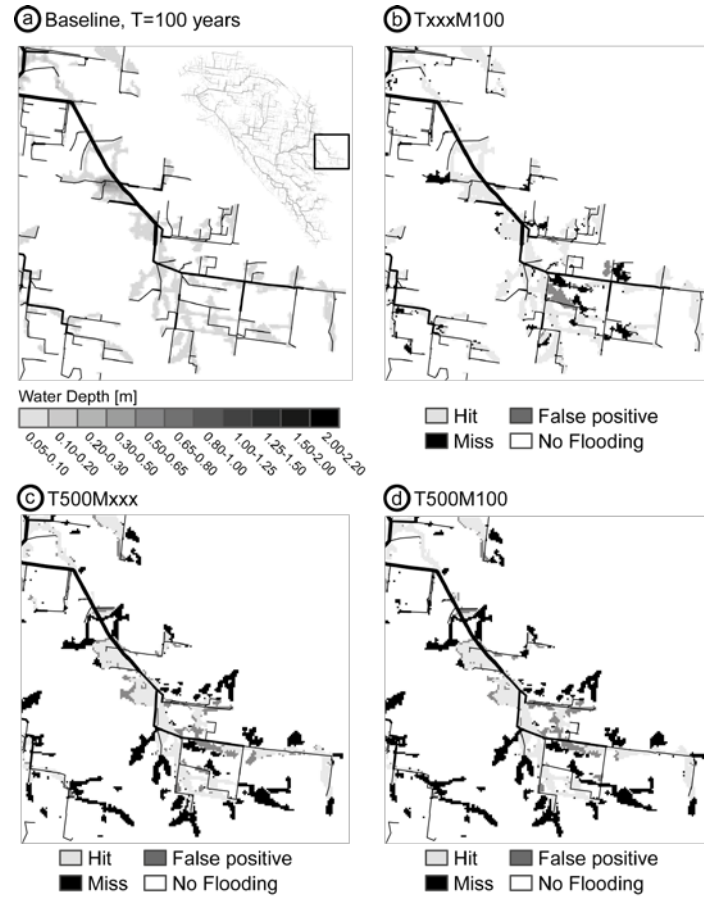


Figure 8: (a) show an overview with the maximum water depth for the baseline during a 100-year event. Figure (b), (c) & (d) show the differences from the baseline in spatial flood results for the TxxxM100, T500Mxxx and T500M100 models, respectively.

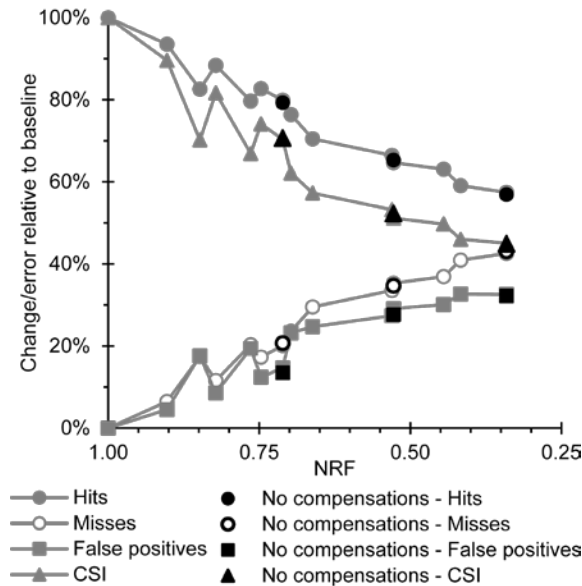


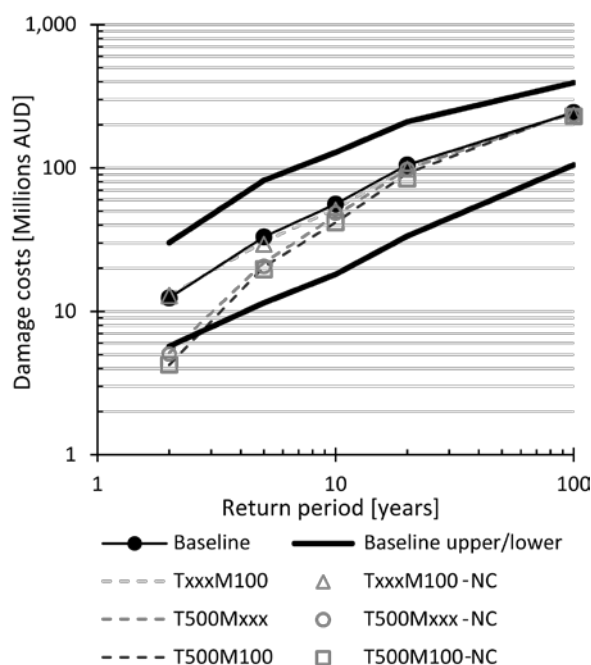
Figure 9: CSI of simplified models along with hits, misses and false positives. Hits and misses add up to 100% while false positives are excess pixels. Models without compensations are shown with black symbols for comparison.

This indicates that flooding may have moved from one location to another. This is also visible in Figure 8 where flooding in trimmed models occurs downstream in the larger branches instead of the outer branches.

329 Inspection of the simulations shows that the spatial changes are in many cases limited to distances of a few
 330 pixels, hence these errors may be of little importance for many applications. This is tested by calculating the
 331 costs of flooding for a range of return periods and by calculating the *EAD* using the approach presented by
 332 Olsen et al. (2015).

333 The total damage cost for each return period is shown in Figure 10, including the variation resulting from the
 334 reference. The simplified models are very similar to the baseline for the return periods of 10-100 years while
 335 cost for the 2 and 5-year return periods are underestimated, especially for models including trimming up to a
 336 diameter of 500 mm.

337



338

339 Figure 10: Total damage costs of flooding for selected models. The baseline variation indicates the variation of the costs by changing
 340 the runoff only, i.e. the uncertainty of the valuation of the damages is not included.

341 In Figure 11, we see significantly lower errors in the *EAD* than the 55% change in *CSI* in Figure 9, thus
 342 supporting the hypothesis that spatial changes have a smaller impact on the catchment-wide risk. As for the
 343 flooded area, the simplified models have a tendency to underestimate the costs of flooding and higher
 344 degrees of simplification lead to larger errors. The differences in error are not the same for merging and
 345 trimming with the merging approach leading to much lower error in *EAD* than trimming. To maintain
 346 accuracy, trimming shall only be applied when merging cannot simplify the model sufficiently, thus a
 347 combination of trimming and merging should be used instead. The changes in *EAD* are generally small
 348 compared to the uncertainties of the parameters used in the cost function (Merz et al., 2010). Additionally,
 349 the impact of the differences in *EAD* will be further reduced in the many applications where it is the

350 difference in *EADs* between different measures that is used as a decision-making criterion. Hence, the
 351 accuracy of the *EAD* appears to be sufficient for decision-making even for very simplified models.

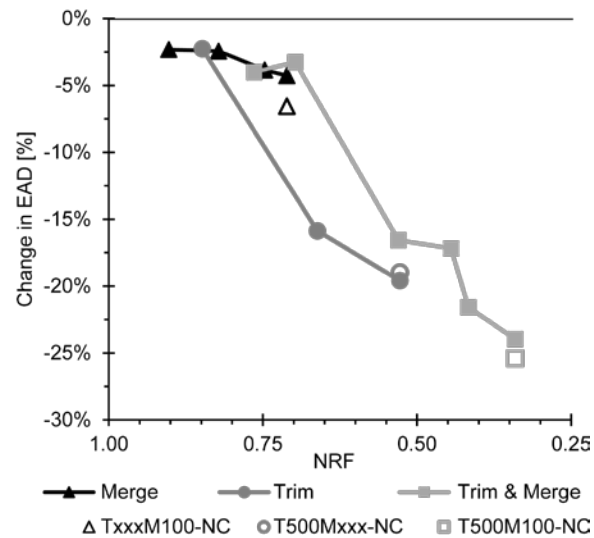


Figure 11: Changes in *EAD* from the baseline of 25.1 million AUD for each of the simplification approaches.

355 Effects of Compensations

356 The influence of the implemented compensations is investigated for all three approaches to validate if the
 357 compensations improve the results.

358 Including compensations for volume loss kept the total network volume deficit within 0.2% compared to 6%
 359 in the non-compensated T500M100 model.

360 In the 1D hydrographs, the peak arrival time and peak flow obtains a better fit to the baseline in the
 361 compensated models. In non-compensated models, the initial peak arrives earlier than in the baseline and
 362 compensated models hence the approach for time-compensation is working as anticipated.

363 Despite a network volume deficit of 4.3% and 5.5% for the non-compensated T500Mxxx and T500M100
 364 models respectively, the 1D/2D water exchange values are better when neglecting the volume
 365 compensations. Additionally, the non-compensated TxxxM100 model yields similar or improved
 366 hydrographs as compared to the compensated model. Thus, it is likely that the manhole size has a more
 367 significant effect on the 1D/2D interactions than the network volume deficit and it may be beneficial to use a
 368 different approach for implementation of volume compensations, or to simply avoid the compensation
 369 scheme.

370 The spatial errors of the non-compensated models are shown as black symbols on Figure 9, and indicate that
 371 compensations for volume losses and travel time are of little importance for the spatial flood distribution. In

372 Figure 11, compensations slightly improve *EAD* in the TxxxM100 and T500M100 models while *EAD* for
373 T500Mxxx is worse than the T500Mxxx-NC model.

374 Overall, the compensations improve the results of the 1D hydrographs and flood area. However,
375 compensations have only slightly positive or a negative effect on results of water exchange, *CSI*, total
376 damage cost and *EAD*. Only when applying the compensations, outflow from the 1D network to the 2D
377 surface varies significantly from the baseline. However, the inflow from the 2D surface to 1D network
378 increase or decrease correspondingly with the changes in outflow, resulting in a net decrease in flooded
379 surface area.

380 When accurate hydrographs are of high priority, compensation for travel time may be justified. The small
381 changes in travel time however have little effect on 2D results. Compensating for volume loss by changing
382 manhole diameters is also not recommended as this leads to decreasing accuracy of the 2D model results.

383 **DISCUSSION**

384 It was possible to reduce the computation time of 1D/2D simulations by 35%, exclusively by modifying the
385 1D hydraulic network model. The overall resulting calculated *EAD* changed remarkably little even when
386 applying quite aggressive model simplifications. However, other metrics varied systematically as a function
387 of the model simplification. Hence, the type and degree of model simplification that can be justified seems to
388 depend on what the model is used for.

389 Even though the calculated hydrographs overall showed good agreement for different levels of
390 simplification, the simplifications proved to have an impact on the 1D hydraulic network. The main change
391 was identified as an overestimation of flow along main branches, occurring mostly when applying merging.
392 The effect may be reduced by increasing energy losses, e.g. by decreasing Manning numbers, where features
393 have been deleted.

394 The simplification of the 1D network model also influenced the exchange between the 1D and the 2D parts
395 of the model, mainly for trimmed models. In general, this led to fewer locations with floods but larger
396 flooding at these locations. This cancellation of errors is the main reason why the overall *EAD* seems to be
397 rather accurate in spite of high degree of model simplification. However, for moderate return periods there
398 will be rather large and systematic differences in the spatial distribution of flooding in the catchment. Since
399 flooding during events with small return periods constitutes a large part of the overall risk, the degree of
400 simplification of the 1D network is important in identifying potential measures to reduce the risk. Hence, the
401 impact of 1D model simplification seems to have the potential of reducing calculation times considerably,
402 but at the expense of less knowledge of where in the catchment the flooding occurs for smaller return
403 periods.

404 It could be studied if including features of the 2D model in the simplification in the 1D model would lead to
405 better results. The starting point could be to put constraints on simplifications close to and in local
406 depressions. For merging, it could be hypothesized that the key would be to include nodes in the depressions,
407 whereas for trimming it might be important to retain links to areas with depressions.

408 **CONCLUSION**

409 In this study, a Simplification Algorithm for 1D Hydraulic network Models (SAHM) is developed as an
410 automatic simplification approach. The resources spend on model simplifications are substantially reduced
411 compared to manual or semi-automatic procedures. Additionally, the procedures are streamlined between
412 users, with a common set of checks conducted prior to removal of a link or node. A guideline of inputs to
413 SAHM, e.g. thresholds depending on the modelling purpose, may be an advantage to avoid over- or under-
414 simplified models. This may be an advantage even when employing only 1D models. However, in our case,
415 the main focus is on how such simplifications impact simulations of pluvial flooding.

416 The simplification of a network with more than 20,000 elements is conducted within a few minutes using
417 merging, trimming or a combined simplification method. Using the developed approach, the computation
418 time for the 1D/2D simulation decreases by 35% after removing 66% of the elements in the 1D hydraulic
419 network model. The simplified models are compensated for volume losses and travel time differences. The
420 approach of implementing compensations for travel time leads to small improvements in 1D hydrographs of
421 the hydraulic network model while compensating for volume losses of deleted features leads to a decline in
422 accuracy of Critical Success Index (*CSI*) and Expected Annual Damages (*EAD*).

423 1D hydrographs of the hydraulic network model show little variation between the baseline and simplified
424 models but overestimation of flow in main branches. Spatial deviations of the 2D flood models are evaluated
425 using the *CSI* and indicate that these models are highly influenced by the level of detail of the 1D hydraulic
426 network. Thus, it is necessary to exercise caution when using simplified 1D/2D urban flood models for flood
427 hazard assessments and design purposes. Calculation of the *EAD* is considerably less sensitive to model
428 simplifications, with merging considerably more accurate than trimming. Suggestions for how the procedure
429 can be improved further are given. For instance, maintaining connection to depressions may be a main
430 objective to improve the accuracy of the reduced model. Overall, it already seems feasible to be able to
431 derive simpler flood models without compromising the accuracy in an unacceptable manner.

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